

Hydrodynamics of a three-phase external-loop airlift bioreactor

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Abstract

The effect the distributing plate orifice diameter, airflow rate, solids loading and solids density on the hydrodynamic characteristics – gas holdup, circulation time and liquid velocity – of a three-phase external-loop airlift reactor was characterized. It was observed that the gas distributor has a small effect on riser gas holdup, circulation time and downcomer liquid velocity. On the contrary, the airflow rate, solids loading and solids density significantly affect the hydrodynamic characteristics of the external-loop airlift reactor.

1. INTRODUCTION

With its increasing applications to biotechnology processes, airlift reactors appear to be one of the most important bioreactor configurations. Airlift reactors are reaction vessels divided in two sections - the riser, where the gas is injected, and the downcomer – and are classified according to the way in which the loop for circulating the liquid is arranged: the internal-loop airlift reactors contain the riser and the downcomer in the same column and in the external-loop reactors the downcomer and the riser are separate tubes put up side by side and connected at the top and at the bottom. Characteristic properties of external-loop airlift reactors are (Onken and Weiland, 1983): (a) complete degassing of the liquid at the top, what prevents accumulation of CO₂ in the fermentation liquid and the reduction of the driving force for oxygen transfer due to entrainment of bubbles lean in oxygen; (b) no zones of irregular flow at top and bottom of fermenter; (c) easy removal of heat from the fermenter; and (d) easy measurement and control of liquid circulation rate in the downcomer without complications arising from the gas content.

External-loop fermenters have frequently been used in investigations of reactor behaviour in laboratory, bench-scale and pilot-plant installations, apparently because of the well-defined conditions in the system. However, the amount of generalized information available is small. This is due to the fact that, for a given superficial gas velocity value, any variation of gas or liquid physical properties, downcomer and riser cross-section ratio, top and bottom riser and downcomer connecting sections geometry, phase separation conditions, liquid volume, reactor height or gas distributing plate, generates a modification in liquid velocity and gas-holdup (Bentifraouine *et al.*, 1997). The complexity increases when a third phase (solid) is added to the system. The majority of data has been obtained for air-water systems that are not necessary representative of fermentation processes, which are characterized by the presence of a solid-phase slightly denser than water and where high concentrations of solids may occur. Kochbeck *et al.* (1992) observed that liquid velocity in an external-loop airlift reactor is drastically reduced by the presence of high density solid particles. Working with low density solids and with high amounts of solids (till 30% v/v), Freitas *et al.* (1997) found that solids loading and density have a considerable influence on gas holdup, liquid velocity and mixing time of an internal-loop airlift reactor with a degassing zone.

Parameters of the gas distributing system, in particular free plate area and orifice diameter, have been shown to influence strongly the gas holdup values in bubble columns (Kastánek *et al.*, 1993), once bubble size is affected. Gas holdup in an airlift reactor is a parameter of great importance, not

only for its effect on the circulation rate of the liquid but also for its consequence on gas residence time, oxygen transfer and liquid mixing. However, relatively little attention has been paid to the effect of gas distribution in airlift reactors and there is no data published about its influence on the performance of three-phase reactors. For gas-liquid systems, Merchuk (1986) reported, for an external-loop airlift reactor, that there was no difference in the gas holdup and liquid velocity for different holes diameters of the distributing plate. Also for a two-phase system and an external-loop airlift reactor, different results were obtained by Snape *et al.* (1992) when investigating the effect of the distributing plate geometry on gas holdup and liquid velocity. They found that the plate with 0.5 mm orifices had a markedly different behaviour than the plates with higher orifices diameters while only slight increase of gas holdup and liquid velocity with decreasing orifice diameter was observed in the range of orifice diameter 1.0 mm to 3.0mm.

In order to obtain further information about the behavior of three-phase external-loop reactors working with low density particles, the effect of airflow rate, solids loading, solids density and orifice diameter of the distributing plate on riser gas holdup, downcomer liquid velocity and circulation time were systematically studied.

2. EXPERIMENTAL

Experiments were performed in a glass wall external-loop airlift reactor with a working volume of 60 l (schematically depicted in Figure 1). Downcomer and riser diameters are 0.05 m and 0.158 m, respectively, with 2.07 m of height. The height and the diameter of top section are 0.36 m and 0.158 m, respectively, with a contraction that connects to a bend with 0.107 m diameter. The bottom section has the same diameter as the downcomer. The downcomer flow joins the riser 0.05 m above the distributing plate.

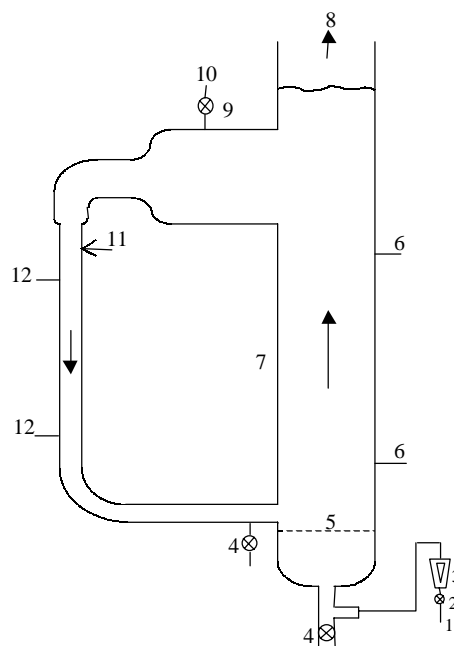


Figure 1 – Schematic representation of the experimental airlift reactor: 1-air feed; 2-regulation valve; 3- rotameter; 4-exit valve; 5-sieve plate; 6-pressure taps; 7-reactor vessel; 8-air vent; 9-valve; 10-water feed; 11-tracer injection; 12-measuring electrodes

Air was used as the gas-phase and injected through perforated plates with a constant free plate area ratio $\phi = 0.2\%$ and hole diameters of 0.5 mm, 1.0 mm and 1.6 mm. The airflow rate was varied between 2100 l/hr and 11800 l/hr corresponding to riser superficial gas velocities, based on the riser cross-section area, between 0.03 m/s and 0.17 m/s, respectively.

Water was used as liquid-phase and Ca-alginate beads, with two different densities, were used as solid-phase and prepared according to the procedure described by Vicente and Teixeira (1995). The mean diameter and density of the “low density solids” (LD) were (2.131 ± 0.102) mm and (1023 ± 1) Kg/m³, respectively, and the values for the “high density solids” (HD) were (2.151 ± 0.125) mm and (1048 ± 1) Kg/m³. For each type of solids, solids loading applied was 0%, 5%, 10%, 15%, 20% and 30% (v/v).

The average volumetric riser gas holdup (ε_{gr}) was calculated from the manometric measurements of hydrostatic pressure in the riser.

Two identical conductimeters equipped with conductivity probes, separated by 1.56 m, were used to characterize the liquid-phase flow in the downcomer. For each set of experimental conditions, a pulse of saturated potassium chloride solution (KCl) was injected, at time zero, into the downcomer, 0.285 m above the top conductivity probe. The amount of KCl added was small enough not to affect the coalescence behaviour of the gas-liquid system (Zahradnik *et al.*, 1995). The data acquisition was stopped once a constant conductivity value was achieved. The responses of the two probes were transmitted to a computer by a data acquisition system. Three replicates were made for each set of experimental conditions.

The downcomer linear liquid velocity (v_{ld}) was calculated dividing the distance between the two probes by the time (Δt) required by the tracer to travel from one to the other.

The circulation time (t_c) was computed by averaging the time spans between maximum consecutive peaks in the conductivity probe response curve and it was obtained independently for each of the two conductivity probes. Its final value, for each set of experimental conditions, is the average between the values registered by the two probes in the three replicates made.

3. RESULTS AND DISCUSSION

3.1. Gas holdup

Gas holdup is one of the most important parameters characterizing bubble bed hydrodynamics. Its value determines the fraction of gas in the bubble bed and thus the residence time of phases in the bed, for given values of gas flow rates (Kastánek *et al.*, 1993). Moreover, the difference between gas holdup in the riser and in the downcomer is responsible for the circulation in the reactor. In this work, gas holdup was measured in the riser, for different experimental conditions. Figure 2, in which values of riser gas holdup (ε_{gr}) are plotted, for the two solids density studied, as a function of riser superficial gas velocity (u_{gr}) and solids loading, represents the effect of the distributing plate orifice diameter on ε_{gr} . It can be seen that, in all situations, riser gas holdup increases with riser superficial gas velocity. For water (0% of solids), the distributing plate of 0.5 mm orifices shows a different behaviour when compared with the other two plates (similar to the results obtained by Snape *et al.*, 1992). Gas holdup increases rapidly with gas superficial gas velocity, appears to be reaching a stationary value and then increases again. These changes of slope in the relation between riser gas holdup and riser superficial gas velocity and the existence of an almost plateau-like transition region between 0.03 m/s and 0.113 m/s can be ascribed to the change of bubbling mode in the riser, analogous to the transition between homogeneous and heterogeneous bubbling regimes commonly reported for bubble column reactors (Kastánek *et al.*, 1993). However, the difference in gas holdup is smaller in the airlift than in the bubble column (as reported by Snape *et al.*, 1995), probably because the superimposed liquid circulation reduces, but does not completely suppress, the influence of plate geometry on bubbling regime. The transition is less pronounced for 1.0 mm holes and does not exist for 1.6 mm holes or three-phase systems, for which gas holdup increases almost linearly with riser superficial gas velocity.

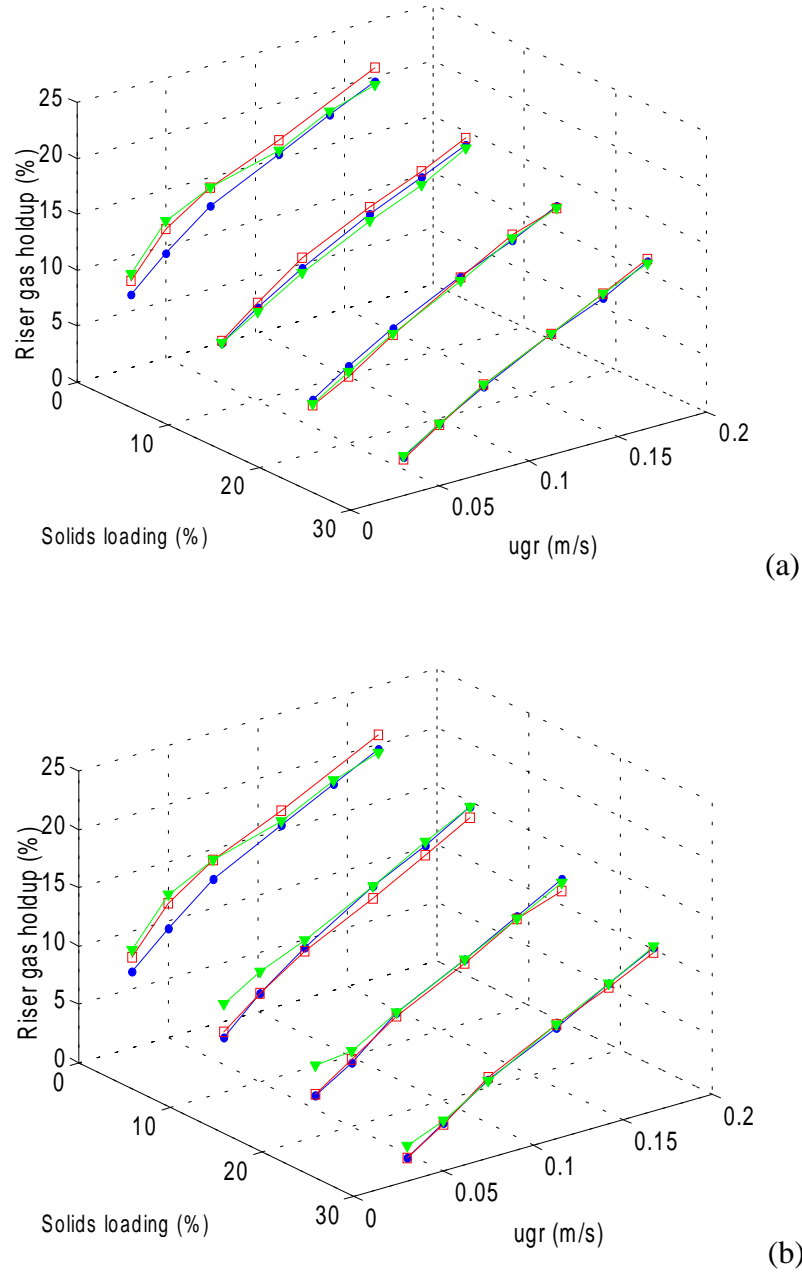


Figure 2 – Influence of solids loading and riser superficial gas velocity (u_{gr}) on the riser gas holdup, for three distributing plate orifice diameters (● - 1.6 mm; □ - 1.0 mm; ▼ - 0.5 mm): (a) Low density solids; (b) High density solids

It can also be seen in Figure 2 that the influence of the orifice diameters of the distributing plates on riser gas holdup is not very significant. For the two-phase system (0% of solids) and the lower solids loading, the increase of orifice diameter leads to a decrease in riser gas holdup but its influence is negligible for solids loading higher than 10%. The orifice diameter of the distributing plate influences the size of the bubbles as they leave the plate, the larger the orifice the larger the initial bubble size. Residence time of the bigger bubbles is lower than of the small ones, once they have higher rise velocities, resulting in lower gas holdup. For high amounts of solids, bubbles can no longer be considered to act independently and bubble coalescence and breakup become important factors – the differences between initial bubble size generated by the three types of the distributing plates are suppressed. Moreover, the suppression of gas distributor effect is enhanced by the influence of the superimposed liquid flow on the flow pattern and on bubble rising velocity

in the riser (Snape *et al.*, 1995). This is the reason why the differences between distributing plates decrease for high values of riser superficial gas velocity.

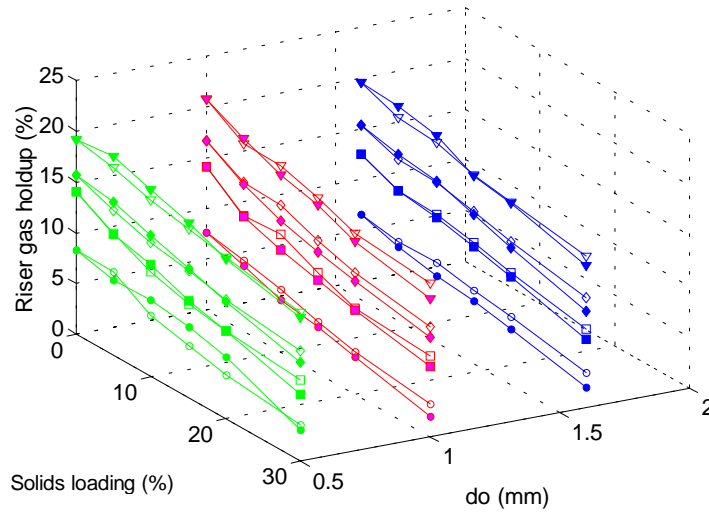


Figure 3 – Influence of solids loading and solids density on riser gas holdup, for three distributing plate orifice diameters (d_o) and for different airflow rates (2100 l/hr: ○ - LD, ● - HD; 5300 l/hr: □ - LD, ■ - HD; 8000 l/hr: ◇ - LD, ◆ - HD; 11800 l/hr: ▽ - LD, ▿ - HD)

Figure 3 shows the influence of solids loading and solids density on riser gas holdup, for the three distributing plates used. The effect of solids loading is clear, once the progressive introduction of solids in the system results in a significant decrease of riser gas holdup. This is due to increasing reduction of flow area of the gas and liquid phases and the consequent increase of coalescence. Similar results were obtained by Lu *et al.* (1995), Verlaan and Tramper (1987) and Freitas *et al.* (1997).

Although the small differences observed, it seems that, generally, for orifices of 1.0 mm and 1.6 mm diameter, riser gas holdup decreases with the increase of solids density while, for 0.5 mm orifices, it increases. For solids with higher density, settling velocity is higher what may cause a higher retention of the bubbles as a result of the entrapment of the smaller bubbles formed by the distributing plate of 0.5 mm orifices. The bigger bubbles formed by 1.0 mm and 1.6 mm orifices diameter may suffer an increase of coalescence, with the consequent decrease of gas holdup.

3.2. Circulation time

In Figure 4, circulation time (t_c) is plotted, for both solids density and the three distributing plates used, as a function of riser superficial gas velocity (u_{gr}) and solids loading. For low airflow rates, circulation time is a strong function of the riser superficial gas velocity, decreasing with the increase of the airflow rate. For higher airflow rates, circulation time dependence on airflow rate becomes very small.

In agreement with the results obtained for riser gas holdup (Figure 2), the circulation time is only significantly affected by the distributing plate orifice diameter for low values of solids loading. For 0% of solids, circulation time increases with the orifice diameter and, for 10% of high density solids, circulation time is also lower for the 0.5 mm distributing plate. For higher amounts of solids, the circulation time has not a defined trend, as expected, since the riser gas holdup is also only influenced by the distributing plate for low solids loading. In these cases, as riser gas holdup decreases with the increase of the orifice diameter of the distributing plate, the driving force for liquid circulation becomes smaller and, hence, the circulation time. For high solids loading, probably because of the different amounts of bubbles entered into the downcomer for the three

distributing plates, the difference between riser and downcomer gas holdup is affected in different ways, what could explain the uncertainty of the influence of the distributing plates on the circulation time in these cases. However, the differences observed are very small what leads us to conclude that the distributing plate orifice diameter has a small influence on circulation time for high solids loading.

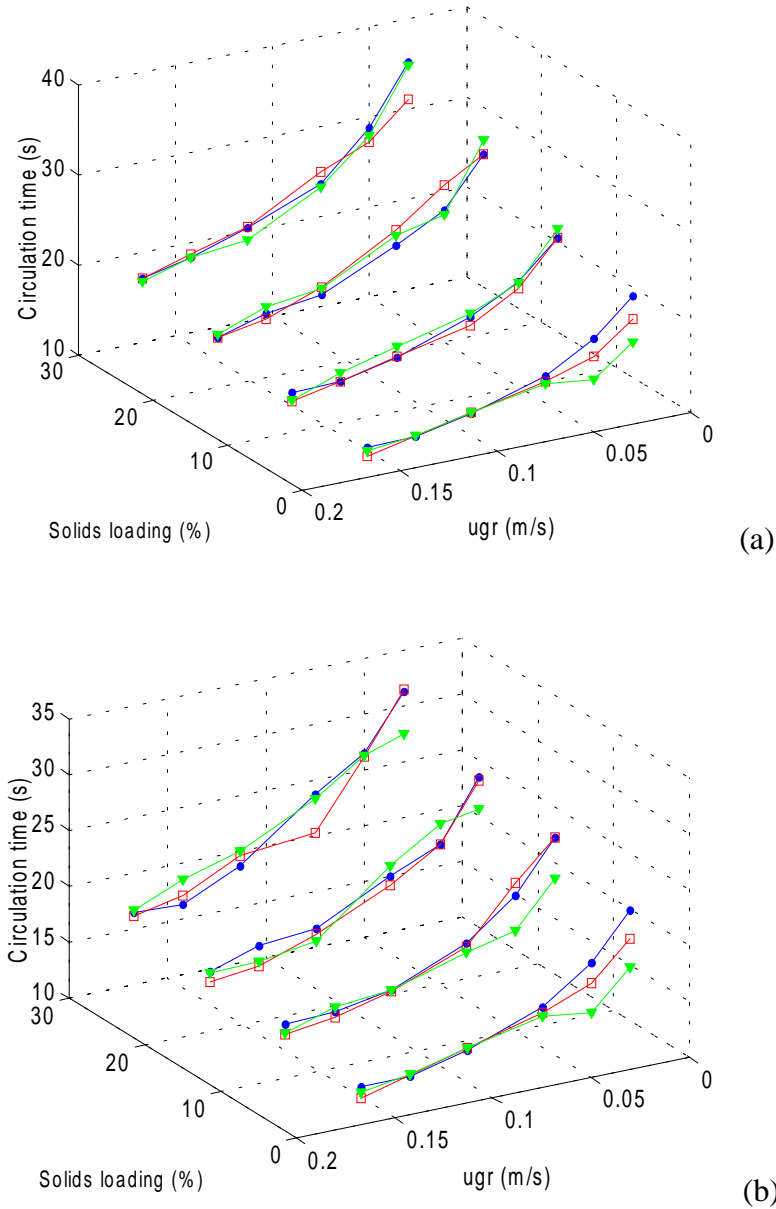


Figure 4 – Influence of solids loading and riser superficial gas velocity (u_{gr}) on circulation time, for three distributing plate orifice diameters (● - 1.6 mm; □ - 1.0 mm; ▼ - 0.5 mm): (a) Low density solids; (b) High density solids

The influence of solids loading and density on the circulation time is represented in Figure 5. The increase of solids loading produces an increase of the circulation time, due to the decrease of driving force for circulation, once riser gas holdup is also reduced by the introduction of solids (Figure 3).

It can also be seen in Figure 5 that the increase in the solids density leads to a decrease of the circulation time, specially for low airflow rates, once for high values of airflow rate the effect of the density is negligible. For the distributing plate of 0.5 mm diameter orifices, this result is a

consequence of the increase in riser gas holdup, responsible for a larger driving force for circulation. The influence of solids density on circulation time is reduced by the increase of the orifice diameter of the distributing plate. Still, even in small amounts, circulation time decreases with solids density for both 1.0 mm and 1.6 mm, what contradicts the decrease of riser gas holdup observed in Figure 3. However, with air bubbles coalescence occurring in the riser and with the corresponding increase of the rising bubble velocity, few bubbles enter the downcomer. Thus, although the fact that downcomer gas holdup in external-loop airlift reactors is usually very small, the difference between riser and downcomer gas holdup seems to increase with the increase of solids density, resulting in a lowering of the circulation time.

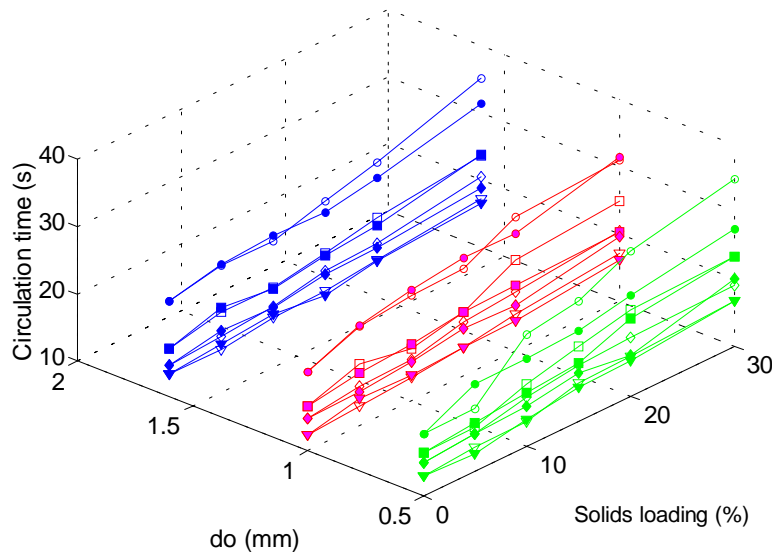


Figure 5 – Influence of solids loading and solids density on circulation time, for three distributing plate orifice diameters (d_o) and for different airflow (2100 l/hr: ○ - LD, ● - HD; 5300 l/hr: □ - LD, ■ - HD; 8000 l/hr: ◇ - LD, ◆ - HD; 11800 l/hr: ▽ - LD, ▿ - HD)

3.3. Liquid velocity

Figure 6 presents the influence of the distributing plate orifice diameter on downcomer linear liquid velocity, for the low solids density. With each experimental data the standard deviation associated is shown. As can be seen, there is no evident effect of the studied characteristics of the distributing plate on the liquid velocity.

In all the cases studied, downcomer liquid velocity responds in a similar way to the aeration rate, increasing with the increase of riser superficial gas velocity, which is an expected result. At small gas throughputs, the gas holdup in the riser increases considerably more with increasing gas velocity than in the downcomer. Thus, the resulting large driving force leads to a large increase of liquid velocity for low superficial gas velocities, whereas at larger gas throughputs the liquid velocity tends to level off (Weiland, 1984).

Figure 7 compares the downcomer linear liquid velocity for high and low solids density allowing for the conclusion that, generally, solids density produces an increase of the downcomer liquid velocity. This is in accordance with what was presented in Figure 5, where circulation time decreases with solids density, once for this to happen downcomer liquid velocity has to increase. Also as for the circulation time, solids density has a lower influence on downcomer liquid velocity for the higher distributing plate orifice diameter.

The influence of solids loading on downcomer linear liquid velocity is also shown in Figure 7. Downcomer liquid velocity decreases with solids loading as a consequence of the increase of bubble coalescence (reflected on the decrease of riser gas holdup shown in Figure 2) and of the

frictional loss caused by the reduction of the flow area of the gas and liquid phases. Similar results were reported by Lu *et al.* (1995).

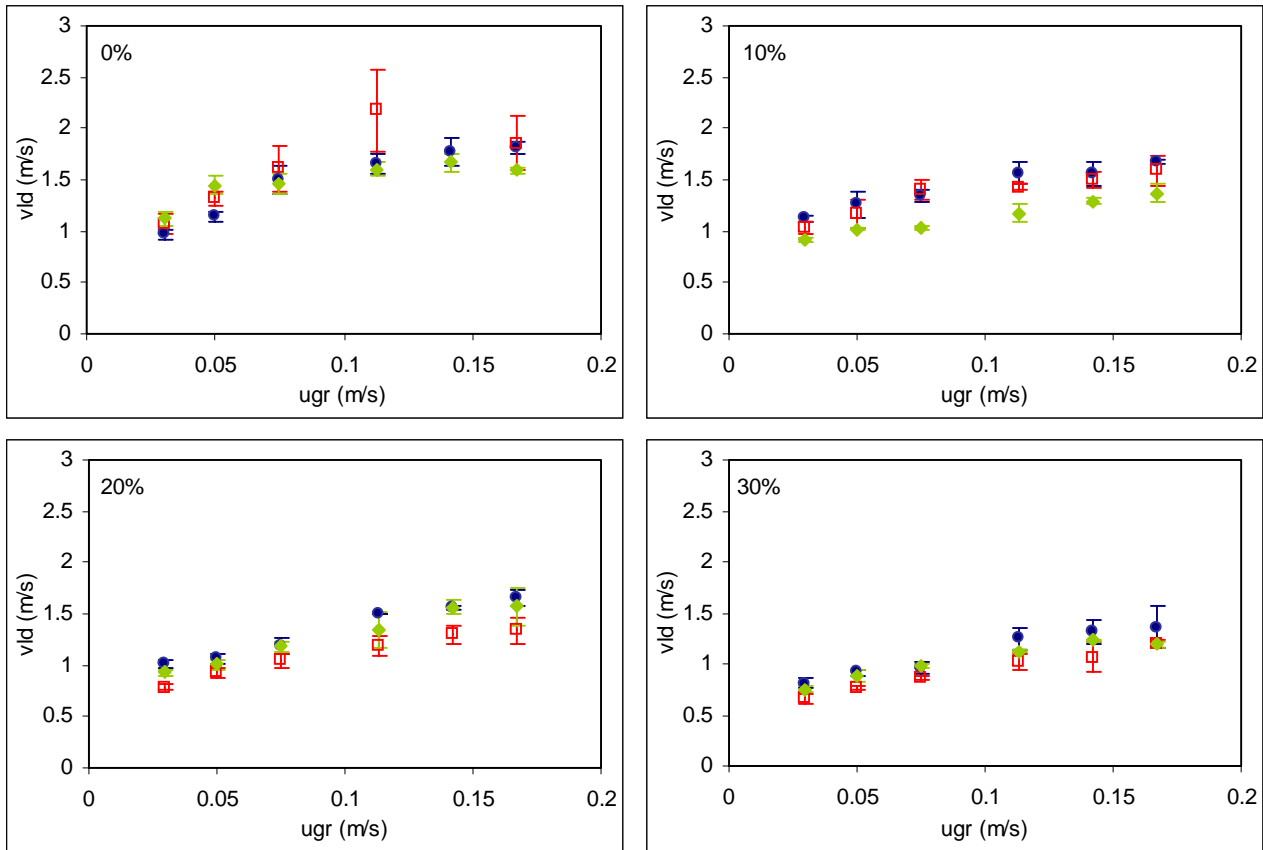


Figure 6 – Influence of riser superficial gas velocity (u_{gr}) on the downcomer linear liquid velocity (v_{ld}), for different solids loading (0%, 10%, 20% and 30% v/v) and three distributing plate orifice diameters (● - 1.6 mm; □ - 1.0 mm; ▼ - 0.5 mm) - Low density solids

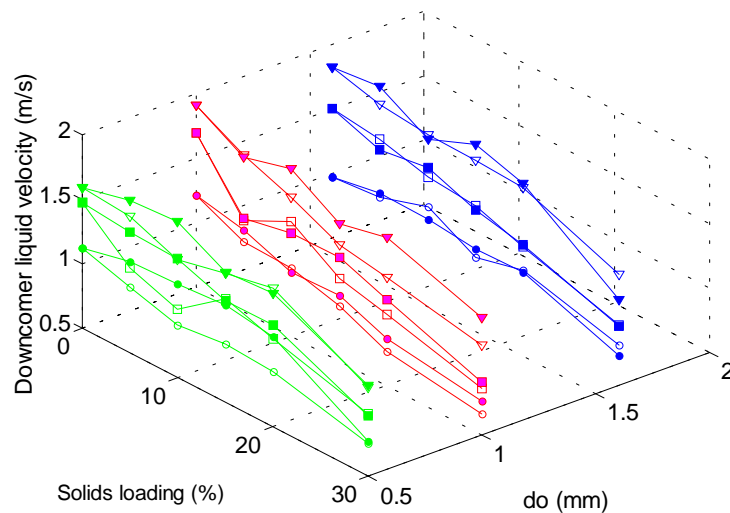


Figure 7 – Influence of solids loading and solids density on downcomer linear liquid velocity, for three distributing plate orifice diameters (d_o) and for different airflow rates (2100 l/hr: ○ - LD, ● - HD; 5300 l/hr: □ - LD, ■ - HD; 11800 l/hr: ▽ - LD, ▼ - HD)

4. CONCLUSION

Experiments were conducted to investigate the effect of the distributing plate orifices diameter, the airflow rate, the solids loading and density on the riser gas holdup, the circulation time and the downcomer liquid velocity of a three-phase external-loop airlift reactor. It was found that the distributing plate orifices diameter has not a significant influence on the parameters studied, being only observed a slight change on riser gas holdup, liquid velocity and circulation time for low airflow rates and low solids loading. This reduced effect of the gas distributor in airlift reactors, when compared with bubble columns, can be ascribed to the influence of superimposed liquid flow on the flow pattern and bubble rise velocity in the riser, enhanced due to the presence of the solid phase. On the contrary, airflow rate and solids loading have a great effect on riser gas holdup, circulation time and downcomer liquid velocity. The increase of airflow rate leads to an increase of riser gas holdup and liquid velocity while the circulation time, consequently, decreases. In opposition, the increasing introduction of solids produces a decrease of the gas holdup and liquid velocity and an increase of circulation time. There is not a well defined trend of the effect of solids density on the studied hydrodynamic characteristics of the three-phase external-loop airlift reactor.

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REFERENCES

- Bentifraouine, C., Xuereb, C. and Riba, J. -P. (1997) An experimental study of the hydrodynamic characteristics of external loop airlift contactors. *J. Chem. Tech. Biotechnol.* **69**, 345-349.
- Freitas, C. and Teixeira, J. T. (1997) Hydrodynamic studies in an airlift reactor with an enlarged degassing zone. *Bioprocess Eng.* **18**, 267-279.
- Kastánek, F., Zahradnik, J., Kratochvil, J. and Cermák, J. (1993) Chemical reactors for gas-liquid systems. Stanek V. editor, Ellis Horwood, New York.
- Kochbeck, B., Lindert, M. and Hempel, D. C. (1992) Hydrodynamics and local parameters in three-phase-flow in airlift-loop reactors of different scale. *Chemical Engineering Science* **47**, 3443-3450.
- Lu, W. -J., Hwang, S. -J. and Chang C. -M. (1995) Liquid velocity and gas holdup in three-phase internal-loop airlift reactors with low-density particles. *Chem. Eng. Science*. **40**, 1301-1310.
- Merchuk, J. C. (1986) Gas hold-up and liquid velocity in a two dimensional air lift reactor. *Chemical Engineering Science* **41**, 11-16.
- Onken, U. and Weiland, P. (1983) Airlift fermenters: Construction, Behaviour, and uses *Advances in Biotechnological Processes 1*. Alan R. Liss, New York, 67-95.
- Snape, J. B., Fialová, M., Zahradnik, J. and Thomas, N. H (1992) Hydrodynamic studies in an external loop airlift reactor containing aqueous electrolyte and sugar solutions. **47**, 3387-3394.
- Snape, J. B., Zahradnik, J., Fialová, M. and Thomas, N. H (1995) Liquid-phase properties and sparger design effects in an external-loop airlift reactor. *Chemical Engineering Science* **50**, 3175-3186.
- Verlaan, P. and Tramper, J. (1987) Hydrodynamics, axial dispersion and gas-liquid oxygen transfer in an airlift-loop bioreactor with three-phase flow. *International Conference on Bioreactors and Biotransformations*, paper I4, 363-373.
- Vicente, A. and Teixeira, J. T. (1995) Hydrodynamic performance of a three-phase airlift bioreactor with an enlarged degassing zone. *Bioprocess Engineering* **14**, 17-22.
- Weiland, P. (1984) Influence of draft tube diameter on operation behaviour of airlift loop reactors. *Ger. Chem. Eng.* **7**, 374-385.

Zahradnik, J., Fialová, M., Kastanek, F., Green, K. D. and Thomas, N. H (1995) The effect of electrolytes on bubble coalescence and gas holdup in bubble column reactor. Chem. Eng. Res. Des. **73**, 341-346.